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INFLUENCE OF MICROSTRUCTURE ON THE FRACTURE TOPOGRAPHY OF TITANIUM ALLOYS

By J. C. Williams^a, R. R. Boyer^b, and M. J. Blackburn^c

ABSTRACT

A survey is presented of the fracture topography observed in titanium and titanium alloys. Ductile fracture by microvoid nucleation, growth, and coalescence is of widespread occurrence in these alloys. It is usually possible to qualitatively relate the dimple size to the macroscopic ductility of the alloy. Titanium alloys may be embrittled by alloying additions that, in most cases, lead to a fine dispersion of second-phase particles. In α -phase alloys, this brittleness is associated with cleavage fracture. However, β -phase alloys, which exhibit cleavage-like macroscopic behavior, show evidence of small dimples when observed using a microscope. Environment often dramatically affects the fracture behavior of titanium alloys, producing low-energy cleavage-like failures in α and β phases, which are normally ductile. We attempt to relate observations of fracture behavior and topography to structural and environmental factors.

INTRODUCTION

The recent resurgence of interest in titanium has resulted in the investigation of many aspects of the mechanical, structural, and chemical behaviors of titanium alloys. One area of obvious importance is the fracture behavior of titanium alloys and the factors that influence it. In this paper, we present information on fracture modes at ambient temperatures that was obtained using standard techniques of electron fractography.

Many titanium alloys are developed for specific applications. For instance, titanium-alloy development has often been directed toward producing an alloy that has specific mechanical properties.

Because nearly all applications require some measurement of macroscopic ductility, it is not surprising that most titanium alloys exhibit both macroscopic and fractographic ductile characteristics. However, it is now known that various factors can result in the embrittlement of titanium alloys; in this paper, we discuss the changes in fracture behavior and appearance that accompany such embrittlement, with the exception of hydrogen embrittlement. The relationship between the structural and environmental conditions that produce brittleness are discussed, and an attempt is made to relate these factors to fracture behavior. Most commercial alloys are used in an $\alpha + \beta$ condition, and in many cases changes in fracture behavior may be attributed to changes in only one of the phases. Thus, in some cases, we chose to illustrate fracture behavior in simpler systems using a binary Ti-Al alloy as a model system for the α phase, and Ti-Mn and Ti-Mo alloys as model systems for the β phase.

The paper is divided into sections that discuss ductile, brittle, environmental, and fatigue failures. This division is somewhat arbitrary because considerable overlap exists between some of these areas. In the final section, some of the structural parameters that influence the types of fracture behavior observed are discussed.

EXPERIMENTAL PROCEDURES

All replicas were prepared by a two-stage technique using cellulose acetate for the first stage and germanium-shadowed carbon for the final stage. Specimens were tested in a wide variety of configurations and under a number of different test conditions, these variables are included when they are relevant to the fracture behavior.

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RESULTS

DUCTILE FRACTURE

Ductile fracture of most α -, β -, and $\alpha+\beta$ -phase titanium alloys occurs by nucleation, growth, and coalescence of microvoids. Figure 1 is an example of this for each type of alloy. There is a correlation between decreasing dimple size and decreasing macroscopic ductility that is similar to that of other materials (1). This correlation can be shown in several alloys in which the flow and fracture behavior can be changed by heat treatment. Figures 2, 3, and 4 illustrate this trend for three different heat-treat conditions of each of three alloys. Similar trends may be seen when comparing the fracture surfaces of different alloys with the same phase structure but different mechanical properties. For example, compare Figures 2(a) and 3(b). In this example, the Ti-Mo and Ti-Mn alloys contain the ω phase on quenching; however, the dimple sizes observed do not correlate with the particle spacing. In fact, it is usually impossible to correlate dimple size in any alloy with any features observed using a microscope. In other alloys, e.g. iron- and aluminum-base alloys (2), many dimples contain features that are identified as inclusions or precipitates that act as void nucleation sites. Such features are almost never observed in titanium alloys, and thus the nucleation of voids is rather difficult to explain. The dimple size appears to be orientation dependent. A five-fold variation in dimple size between two adjacent α -phase grains is shown in Figure 5. These variations complicate absolute correlation between dimple size and macroscopic ductility.

An alternate form of ductile fracture is observed in α -phase alloys of low yield strengths and work hardening rates, such as relatively pure (<1500 ppm oxygen) unalloyed titanium. This type of fracture is characterized by extensive regions of serpentine glide, as illustrated in Figure 6. Such fracture behavior is associated with very ductile macroscopic behavior (3).

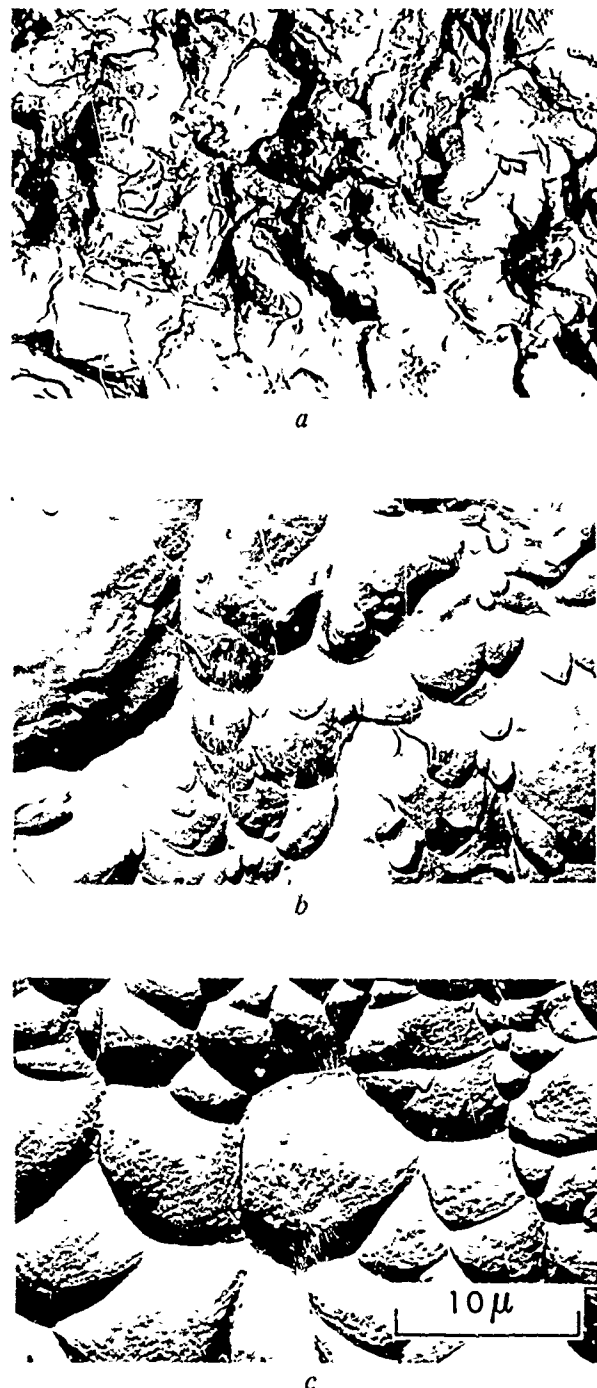
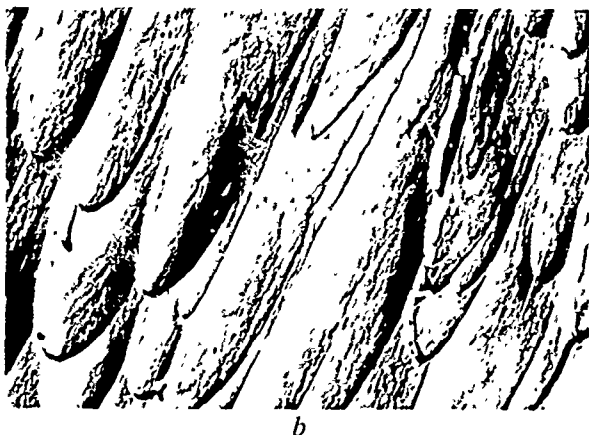


Figure 1. Examples of dimple rupture in the three categories of titanium alloys: (a) $\alpha+\beta$ alloy; Ti-8Al-1Mo-1V, (b) all- α alloy; Ti-5Al-2.5Sn, (c) all- β alloy; Ti-11.6Mo
3500 X

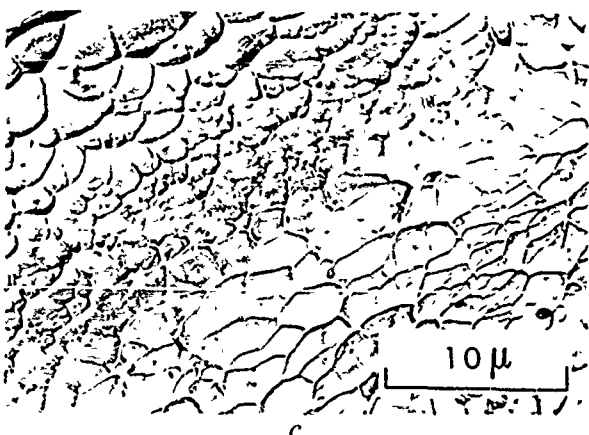
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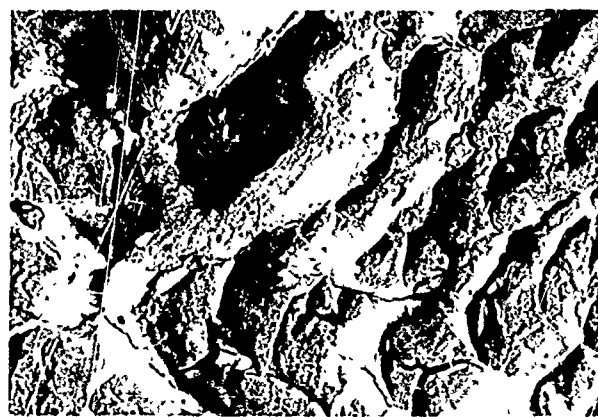


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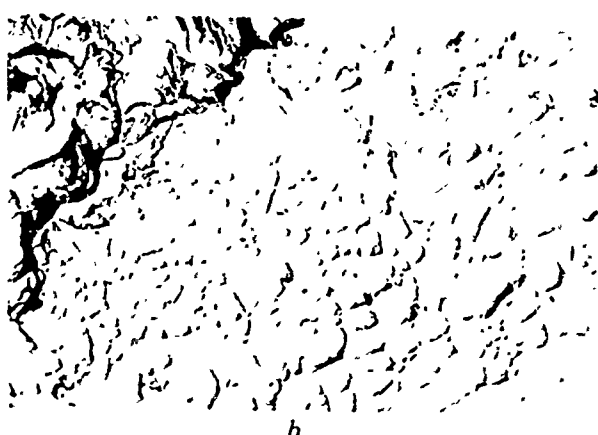


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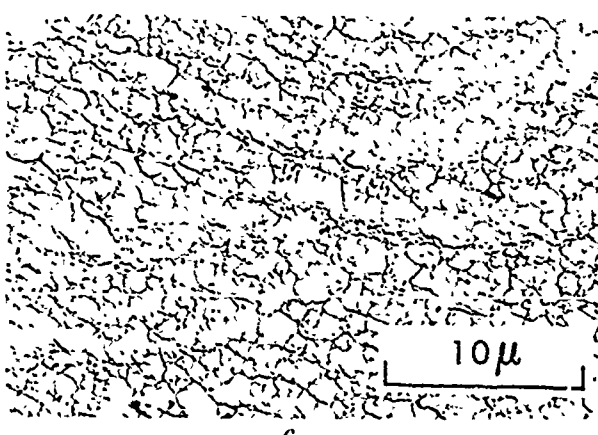
Figure 2. Correlation of dimple size and ductility in Ti-11.6Mo. Ductility decreases from: (a) all- β condition (70% elong.) to (b) α + β condition (14% elong.) to (c) β + ω condition (0% elong.). 3500 X



a



b



c

Figure 3. Correlation of dimple size and ductility in Ti-8Mn. Ductility decreases from (a) β + α condition (22% elong.) to (b) all- β condition (14% elong.) to (c) β + ω condition (0% elong.). 3500 X

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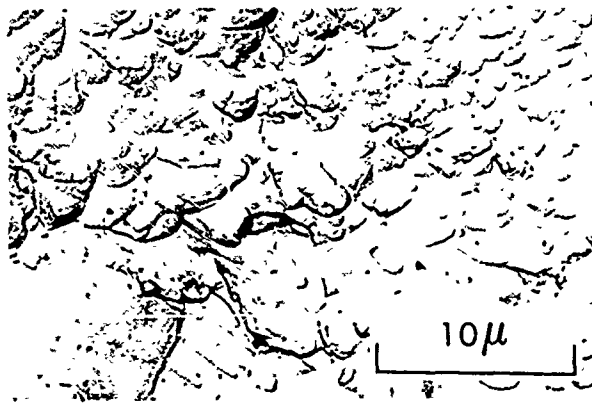
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a



b



c

Figure 4. Correlation of dimple size and ductility in Ti-8Al. Ductility decreases from (a) solution treated at 950°C/W.Q. (~10% elong.) to (b) solution treated at 700°C/W.Q. (~5% elong.) to (c) solution treated at 600°C/W.Q. (~1-2% elong.) 3500 X

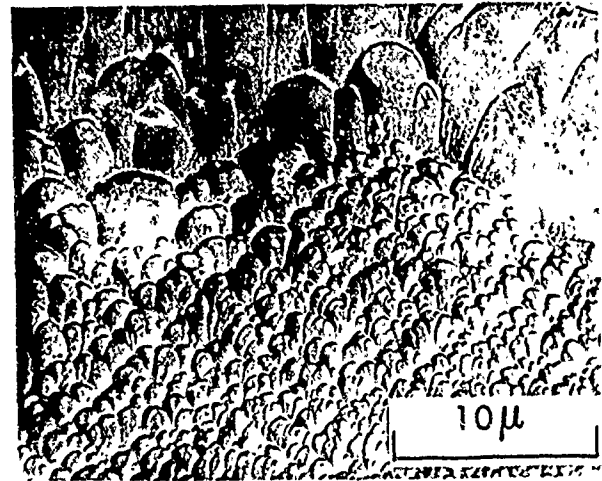


Figure 5. Orientation dependence of dimple size in Ti-8Al 3500 X

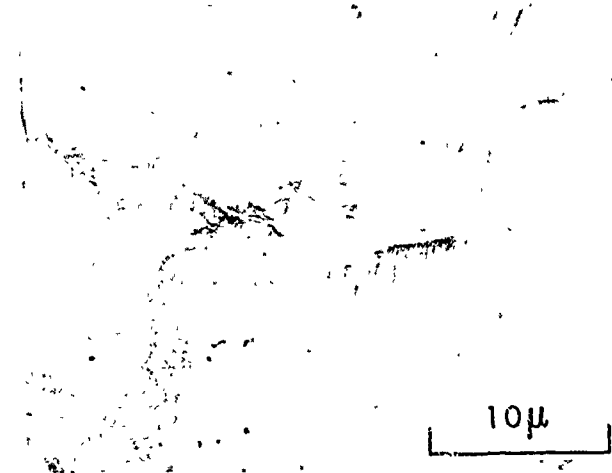


Figure 6. Predominant mode of fracture in commercially pure (A-50) Ti. This mode of fracture is generally known as "serpentine glide" 3500 X

BRITTLE FRACTURE

The occurrence of brittle fracture is undesirable, and thus an understanding of the factors that cause a normally ductile material to fracture in a brittle manner is a prerequisite to successful material applications. Brittle fracture as used here

refers to macroscopic brittle behavior. In some of the following examples, the need for making this distinction is clarified.

α -Phase Alloys

Cleavage fracture of the α phase in air has been observed in several α - and $\alpha+\beta$ -phase alloys tested under various loading conditions. Such behavior is favored by increasing the oxygen or aluminum content of the alloy. In Ti-Al alloys that contain ≥ 7 percent aluminum by weight, precipitation of the ordered α_2 -phase (based on Ti_3Al) occurs during low-temperature aging (4,5). Increasing the oxygen or aluminum content and precipitation of α_2 produces an increase in the yield strength of the alloy and, at the same time, produces planar slip (6). Larger grain sizes, the presence of a sharp notch, increased yield stress, and change in slip mode increase the chance of cleavage fracture. Figure 7 illustrates the cleavage observed in Ti-8Al. In this alloy, the cleavage plane has been established (6) as the $(10\bar{1}7)$ or the $(10\bar{1}8)$. It can be seen that the cleavage fracture in this titanium alloy exhibits many of the features observed in other metals, such as cleavage steps and river patterns. Such irregularities are produced by interaction of a moving crack with structural imperfections in the material such as grain boundaries and screw dislocations (7).

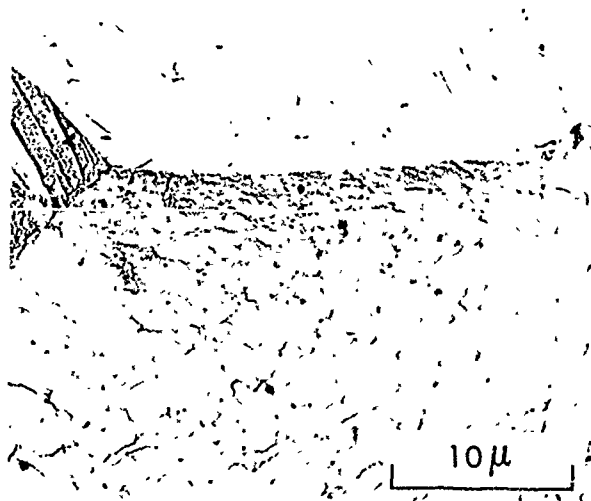


Figure 7. Cleavage in a large-grained, Ti-8Al notched tensile specimen failed in air. 3500 X

β -Phase Alloys

Marked embrittlement of the β phase occurs if a large-volume fraction of small second-phase particles (either α or ω) is formed on aging at low temperatures. The ω phase is a transition precipitate that forms during low-temperature aging of metastable β -phase alloys, such as Ti-8Mn and Ti-11.6Mo, and the metastable β phase of a number of $\alpha+\beta$ -phase alloys. Specimens of Ti-Mo or Ti-Mn quenched from the β -phase field and subsequently aged at 400°C , to produce the ω -phase, exhibited essentially no macroscopic ductility. Specimens appeared by visual examination to have failed by cleavage as shown in Figure 8. Fractographic examination of these specimens, however, showed evidence of microscopic ductility in the form of small dimples as illustrated in Figure 9(a). Such features may have arisen through cracking on various levels and propagation of such microcracks toward the macroscopic crack. This type of fracture has been observed in plexiglass (8). However, the appearance of the dimples observed in Figure 9(a) is not consistent with this process, because these dimples appear to occur on a smooth fracture plane with a constant shape, whereas the dimples observed in plexiglass are randomly above and below the macroscopic fracture plane. Some fractures with a stepped appearance are observed in Ti-Mn alloys, and such steps suggest some crystallographic dependence of the fracture plane. Figure 9(b) shows an example of such a fracture.

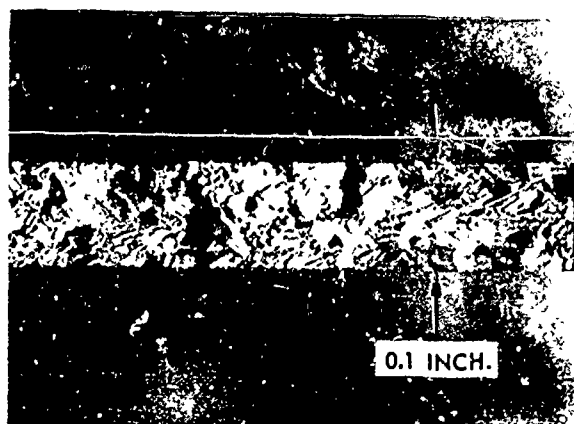


Figure 8. Optical fractograph of Ti-8Mn brittle failure in air (notched tensile specimen in $\beta+\omega$ condition). 8 X

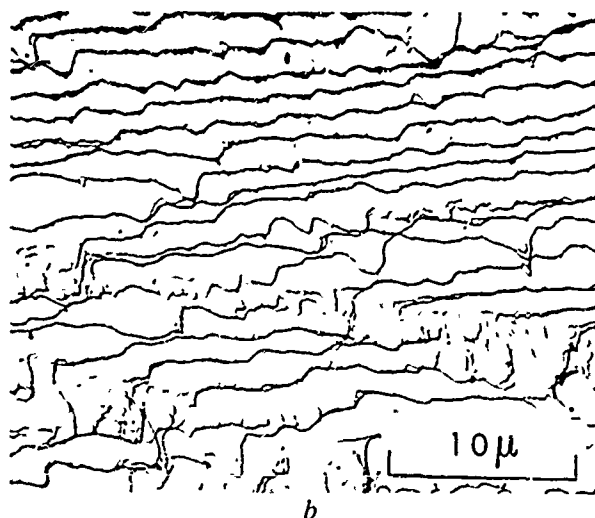
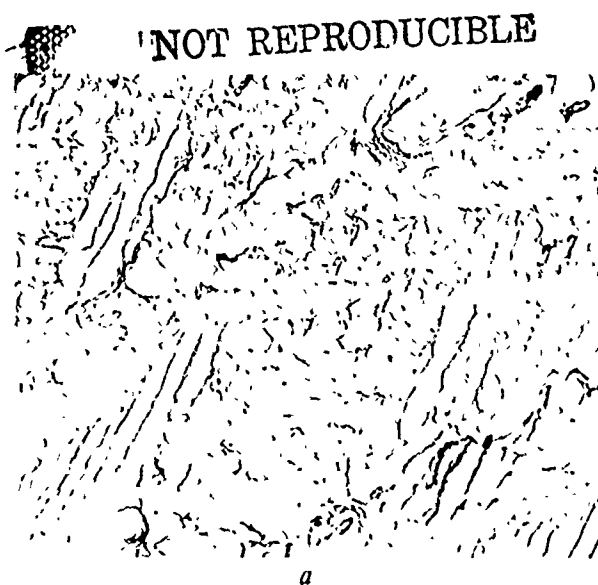


Figure 9. Very fine dimples observed fractographically in Ti-8Mn brittle failure.

3500 X

$\alpha + \beta$ -Phase Alloys

Some instances have been observed where brittle failure of only the α or the β phase occurs. However, in these cases, the appearance of the brittle phase is quite similar to that observed in single-phase α or β alloys, and the conditions in which this occurs are comparable to those that cause embrittlement of the single-phase alloys. Examples of this behavior occur when ω is formed in the β phase of Ti-4Al-3Mo-1V and

when α_2 (Ti₃Al) precipitates in the α phase of Ti-8Al-1Mo-1V. In each case, the β or the α phase is embrittled, whereas the remaining phase is unaffected.

THE EFFECT OF ENVIRONMENT ON FRACTURE BEHAVIOR

Combined action of stress and an active environment (e.g. an aqueous 3.5-percent NaCl solution) can result in the brittle failure of alloys that exhibit ductile behavior in air. Such behavior is known as stress-corrosion cracking. In general, the susceptible single-phase alloys of the α or β type fail in a manner that closely resembles cleavage fracture.

The same factors that promote cleavage of the α phase in air also cause it to be more susceptible to cleavage failure in an active environment. In most cases of aqueous stress-corrosion cracking of α -phase alloys, the specimen configuration and stress conditions are quite stringent. Thus, the presence of a notch and the existence of plain strain at the crack tip are required for failure by stress-corrosion cracking. In organic solvents, these conditions may be relaxed, and stress-corrosion cracking occurs on unnotched specimens. Figure 10 illustrates the appearance of failure by stress-corrosion cracking in a notched Ti-8Al alloy specimen. Failure of the α phase in a predominately α -phase alloy at low stress intensity (K) levels occurs by cleavage. However, as the stress intensity level approaches the value for unstable crack propagation (K_{IC}), the amount of ductile tearing observed increases. This is illustrated in Figures 11(a) and 11(b). A similar cleavage-type fracture was observed in Ti-13V-11Cr-3Al in the β -quenched condition (Figure 12). The occurrence of environmental cracking in this alloy does not appear to be as sensitive to loading conditions, because the presence of notch or plain-strain conditions is unnecessary.

In addition to stress-corrosion cracking of single-phase α and β alloys, there are several multiphase alloys in which only one phase is susceptible. In commercial Ti-Al-Mo-V or Ti-Al-V ($\alpha + \beta$) alloys

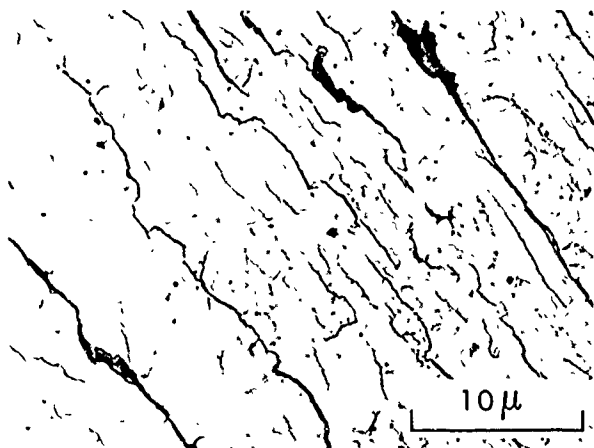


Figure 10. Stress-corrosion failure in a Ti-8Al notched specimen failed in 0.6MKI. 3500 X

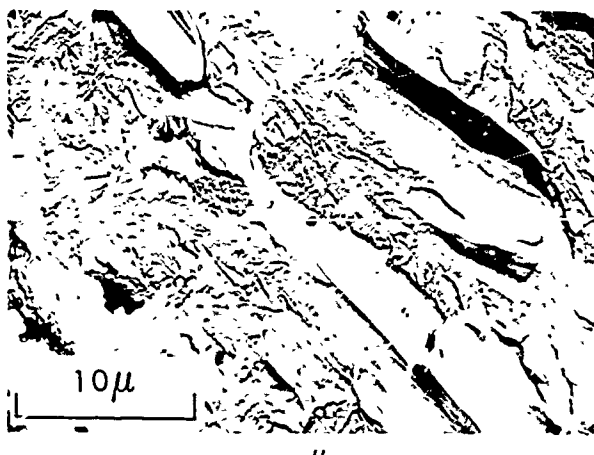


Figure 11. Alteration of fracture topography in Ti-8Al-1Mo-1V by variation of applied stress intensity (K). (a) low K; (b) high K 3500 X

(e.g. Ti-6Al-4V) that contain ≥ 6 percent aluminum by weight, only the α phase is susceptible to environmental cracking, as shown in Figure 13. In contrast, Ti-13V-11Cr-3Al exhibits the opposite behavior in that only the β phase fails in a brittle manner. Thus, aging to produce the α phase results in decreased susceptibility (9). Figure 14 illustrates the failure by stress-corrosion cracking of the β phase in the Ti-8Mn alloy cooled from 900°C to 700°C to produce a Widmanstatten precipitate of the α phase. It is not clear from the micrograph that the α phase is susceptible to stress-corrosion cracking although other observations indicate that it may not be (10).

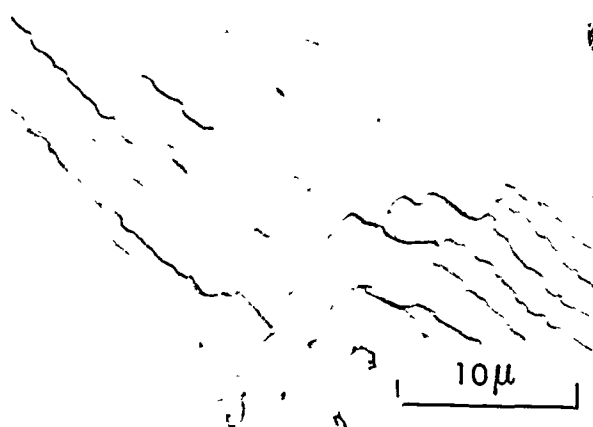


Figure 12. Stress-corrosion failure in Ti-13V-11 Cr-3Al in all- β condition failed in 0.6M KCl. 3500 X

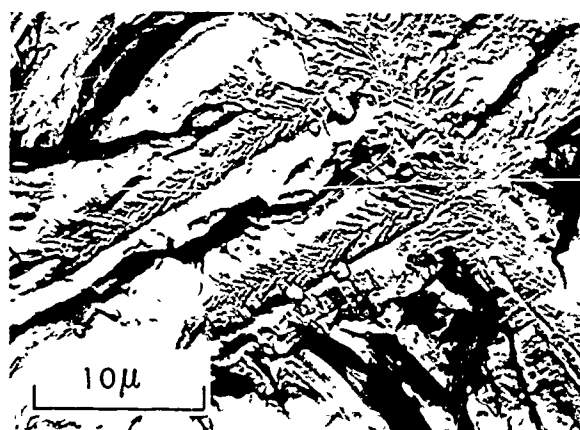


Figure 13. Stress-corrosion failure in Ti-6Al-4V illustrating cleavage in the α phase and ductile fracture in the β phase, failed in 0.6M NaCl. 3500 X

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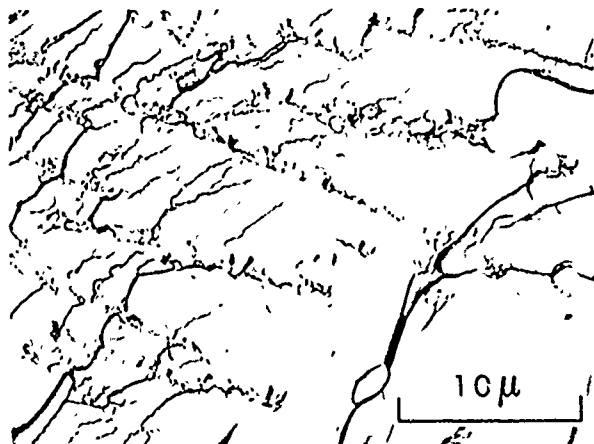


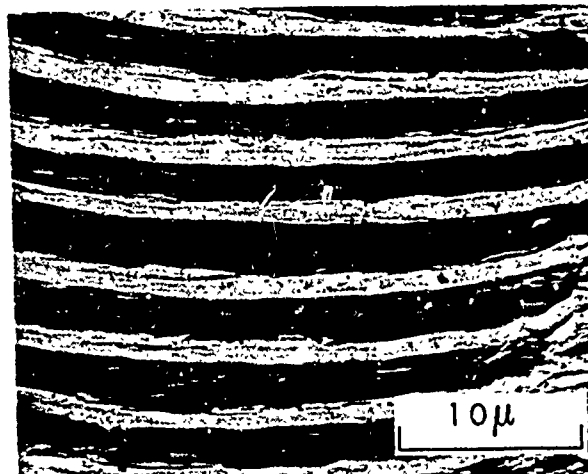
Figure 14. Stress-corrosion failure in Ti-8Mn illustrating cleavage in the β phase separated by bands of α that failed in a more ductile manner in 0.6M KCl. 3500 X

FATIGUE FRACTURE

Only a very limited number of observations on fatigue failure are included here. Fatigue crack propagation in α -, β -, and $\alpha+\beta$ -phase alloys is accompanied by development of fatigue striations present in other alloys (2,11). The striations that occur in the α -phase alloys appear to be strongly orientation dependent, often changing directions markedly when the crack front crosses a grain boundary. Figures 15(a) and 15(b) show the striations observed in α - and β -phase alloys. In brittle Ti-Al alloys aged to produce α_2 and in β -phase alloys aged to produce ω , crack propagation under cyclic loading occurs by cyclic propagation of a crack that extends a large distance in each stress cycle. Fractographic examination shows fractures produced under these conditions appear to be identical to the brittle tensile fractures described previously.

DISCUSSION

This section relates the above observations on fracture behavior and topography to various structural parameters.



a



b

Figure 15. Ductile fatigue striations in (a) Ti-8Al (all- α alloy) and (b) Ti-13V-11Cr-3Al (all- β alloy). 3500 X

The ductile fracture of α -, β -, and $\alpha+\beta$ -phase alloys is shown to occur predominantly by a microvoid coalescence mechanism, but some examples of more ductile behavior were observed in the relatively pure, low-strength α phase. Microvoids are generally considered to be nucleated at inclusions or second-phase particles (2). No such inclusions are observed in titanium because of its reactivity, and the occurrence of a microvoid coalescence fracture is thus rather difficult to explain, especially in single-phase alloys. We can only suggest that a more general type of microvoid nuclei must be operative in this

case. The absence of microvoid nuclei may possibly explain why alternating shear fracture, which is characterized by serpentine glide, is frequently observed in the low-strength α phase. There is a continuous change in fracture behavior of the α phase: alternating shear at low strengths, microvoid coalescence at intermediate strengths (decreasing dimple size with increasing strength), and cleavage fracture at high strengths.

Cleavage fracture of the α phase becomes more prevalent at higher yield stresses, at larger grain sizes, in the presence of a sharp notch, and if slip is localized to planar bands. The yield stress can be increased by alloy additions (notably Al and O) or in a single alloy by precipitation of small particles of a second phase (as in Ti-Al) during low-temperature aging, these compositional factors also promote planar slip. Similar structural parameters are shown to increase the tendency for cleavage fracture in a number of alloy systems (12,13,14). Cleavage cracks are generally assumed to propagate if the resolved normal stress on the cleavage plane exceeds the cleavage stress. In Ti-Al alloys, the cleavage plane has been established as being near $(10\bar{1}7) - (10\bar{1}8)$ and, in this case, a large resolved normal stress on these planes also results in a low resolved shear stress for $\langle 11\bar{2}0 \rangle$ slip on any plane, making the occurrence of cleavage relatively sensitive to preferred orientation. This orientation dependence accounts in part for the observation of mixed cleavage and ductile fracture at intermediate yield stresses or with small grain sizes.

The fracture topography of macroscopically brittle β -phase alloys differs markedly from the cleavage fractures associated with brittle fracture of the α phase. The dimples observed in such cases are small and shallow. The observed embrittlement is associated with formation of a high-volume fraction of small (100 to 1,000 Å) dispersed precipitates (15). Such precipitation can raise the yield strength to $>220,000$ psi in Ti-8Mn and, although grain size and the presence of a notch may be important for brittle failure at intermediate strengths, at these high strengths the alloy is brittle even when tested in compression.

Various other heat treatments can produce structures that have lower strength with improved ductility, and the β -phase alloys are in general characterized by a wide range of mechanical properties attainable by heat treatment. Thus, it is usually possible to avoid such embrittlement by exercising care in heat treatment and service temperature.

It is shown that the combined action of stress and an active environment can result in brittle fracture of the α or the β phase in a variety of alloys. Stress-corrosion-cracking failures of the α phase closely resemble cleavage fracture produced in air; furthermore, the various metallurgical factors that promote cleavage also increase susceptibility to stress-corrosion cracking. Possible mechanisms of such environmental embrittlement have been presented elsewhere (6,16). The structural factors that influence susceptibility of a β -phase alloy appear to be more complicated, as these alloys are usually in their most ductile condition when susceptible to stress-corrosion cracking. There is some evidence that planar slip is observed in susceptible alloys, which may be one structural parameter of importance. It is suggested, however, that the electrochemical properties of the β phase may also be an important factor in determining susceptibility.

Tables I and II summarize the influence of the various constituents that occur in titanium alloys on fracture behavior. Structural parameters such as grain size, phase morphology, etc., have not been included. The phase nomenclature is that used in an earlier paper (17), which also gives more details of the heat treatments that produce these phases in some commercial alloys.

ACKNOWLEDGMENT

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Table I. Summary of the Influence of Structure and Environment on the Fracture Behavior of Titanium Alloys—Primary Constituents

Phase	Composition	Structure	Size*	Type of Fracture	
				Air	Influence of Environment Aqueous + Cl ⁻ , Br ⁻ , I ⁻
α	Ti	hex.	$>\mu$	Microvoid or serpentine glide	None
	+O			Cleavage $>0.7\%$	Cleavage $>0.35\%$
	+Al			Cleavage $>12\%$	Cleavage $>5\%$
β	Ti-Mo Ti-Mn Ti-8Al-1Mo-1V	bcc	>5	Microvoid	None
					None at 8% Mn Cleavage
α'	Formed in Ti-8Al-1Mo-1V and Ti-6Al-4V	fcc or fct	0.1μ (plate size); $>\mu$ (colony size)	Microvoid	None
α''	Formed in many alloys on quench- ing from β field	hex.	0.3μ (plate size) $>\mu$ (colony size)	Microvoid	Little in many commer- cial ($\alpha + \beta$) alloys Cleavage in Ti-Al and Ti-5Al-2.5Sn

*Sizes observed in commercial alloys. This size may be varied over very large ranges by more sophisticated treatments.

Table II. Summary of the Influence of Structure and Environment on the Fracture Behavior of Titanium Alloys—Secondary Constituents*

Phase	Composition	Crystal Structure	Size	Type of Fracture	
				Air	Influence of Environment
α_2	Based on Ti_3Al	hex. DO_{19}	Depends on Al content: in 8%Al—25 - 300 Å	Promotes cleavage	Promotes cleavage
ω	Formed in metastable phase; Ti rich, variable ($c/a \cong 4.1$)	hex.	50 - 1,200 Å	Macrobrittle, micromicrovoid	None
α	Formed on decomposition of β , e.g. Ti-Mo, Ti-Mn, VCA	hex.	100 - 1,500 Å	Macrobrittle, micromicrovoid	None in Ti-Mo; slight effect in Ti-Mn; reduces influence in VCA
			0.5 μ	Macroductile, microvoid	
α	Tempering of α' Ti-6Al-4V, Ti-8Al-1Mo-1V	hex.	500 Å - 1 μ	Microvoid	No influence
β	Formed on tempering of α'' in Ti-6Al-4V and Ti-8Al-1Mo-1V	bcc	500 Å - 1 μ	Microvoid	Increases tendency for cleavage

* Formed by precipitation on tempering

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11. SUPPLEMENTARY NOTES		12. SPONSORING MILITARY ACTIVITY Advanced Research Projects Agency, Department of Defense. National Aeronautics and Space Administration.
13. ABSTRACT A survey is presented of the fracture topography observed in titanium and titanium alloys. Ductile fracture by microvoid nucleation, growth, and coalescence is of widespread occurrence in these alloys. It is usually possible to qualitatively relate the dimple size to the macroscopic ductility of the alloy. Titanium alloys may be embrittled by alloying additions that, in most cases, lead to a fine dispersion of second-phase particles. In α -phase alloys, this brittleness is associated with cleavage fracture. However, β -phase alloys, which exhibit cleavage like macroscopic behavior, show evidence of small dimples when observed using a microscope. Environment often dramatically affects the fracture behavior of titanium alloys, producing low-energy cleavage-like failures in α and β phases, which are normally ductile. We attempt to relate observations of fracture behavior and topography to structural and environmental factors.		

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